# Magnetic-Circuit Units as Adopted by the I. E. C.

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***Synopsis.****—The decisions of the International Electrotechnical Commission (I. E. C.) at Oslo in July 1930, with respect to international magnetic units and unit names, are briefly reviewed.*

*So far as concerns the c. g. s. magnetic units, the decisions appear likely to meet with general favor; but the series is incomplete and might advantageously be supplemented by at least one name—that for the c. g. s. unit of reluctance.*

*The series of units in the practical or volt-ampere-ohm system is also incomplete; but apparently cannot be completed satisfactorily without first deciding two questions: (a) whether the system should be rationalised and (b) whether the m. k. s. or the c. g. s. s. system should be endorsed. It is recommended that these questions be left for the present undecided, until they have been widely discussed, and illustrative literature developed in aid of international decision.*

## C. G. S. MAGNETIC UNITS

At its Plenary Meeting in Oslo, last July, the International Electrotechnical Commission (I. E. C.) adopted resolutions concerning c. g. s. magnetic units, which should enable various ambiguities and inconsistencies to be eliminated in future from international electrotechnical literature of the magnetic circuit.

Firstly, it reaffirmed the *maxwell* as the name of the c. g. s. magnetic unit of flux $\phi$, as adopted at Paris in 1900.

Secondly, it unanimously supported the hypothesis that, for electrotechnical purposes, permeability $\mu_0$ of free space is a quantity having certain physical dimensions, although numerically equal to unity in the c. g. s. magnetic system. Hence, even in a vacuum, or free space, magnetic flux density $\mathcal{B}$ is a different physical quantity from magnetising force $\mathcal{H}$; so that there is both need and justification for their two quantity names (magnetising force and flux density), their two c. g. s. unit names (*oersted* and *gauss*) and their two symbols ($\mathcal{H}$ and $\mathcal{B}$). It was decided to apply the name *oersted* to the c. g. s. magnetic unit of $\mathcal{H}$ and the name *gauss* to the c. g. s. magnetic unit of $\mathcal{B}$. The absolute permeability $\mu$ of a magnetisable substance was decided to have the same unknown dimensions as space permeability $\mu_0$; but the relative permeability of the substance $\mu/\mu_0$ was held to be nondimensional, or a mere numeric.

Thirdly, it adopted the name *gilbert* for the c. g. s. unit of magnetomotive force $\mathcal{F}$.

It may not be amiss to consider the changes that these I. E. C. resolutions probably import into electrotechnical usage.

By far the most important result of the new I. E. C. resolutions is that, if followed, the indefiniteness and ambiguity which have often characterised the literature of the magnetic circuit, on questions of $\mathcal{H}$ and $\mathcal{B}$, can be eliminated. The term *gauss* for instance, can only be used for flux density $\mathcal{B}$.

## I. E. C. RESOLUTIONS IN ENGINEERING WORK WITH C. G. S. MAGNETIC UNITS

In order to conform with the new I. E. C. rulings concerning c. g. s. magnetic units, it seems to be indicated that:

1. When $\mathcal{H}$-$\mathcal{B}$ curves, or "saturation curves," are drawn in the c. g. s. system, for a sample of magnetic material, such as dynamo steel, the abscissas of $\mathcal{H}$ should be in *oersteds* and the ordinates of $\mathcal{B}$ in *gausses.*
2. When $\mathcal{H}$-$\mu$ curves, or "force-permeability" curves are drawn in the c. g. s. system, for a sample of magnetic material, the abscissas should be in *oersteds* and the ordinates in units of *absolute permeability* $\mu$. These units of $\mu$ have no name at present, and their physical dimensions in terms of length, mass and time, have not been assigned. If however, the same curves are to be interpreted as *relative permeability* curves, the ordinates become expressible in $\mu/\mu_0$, and are mere numbers.
3. When $\mathcal{F}$-$\phi$ curves, or "excitation curves," are drawn in the c. g. s. system, for any given magnetic circuit, the abscissas of $\mathcal{F}$ should be in *gilberts* and the ordinates of $\phi$ should be in *maxwells.*

## I. E. C. RESOLUTIONS AND TEXT-BOOK LITERATURE

The equation for magnetisation of materials in the current literature of various countries is well known to be:

$$\mathcal{B} = \mathcal{H} + 4\,\pi\,\mathcal{J} \qquad \text{gausses} \quad (1)$$

where $\mathcal{H}$ is the uniform magnetising force acting upon uniform isotropic material, $\mathcal{J}$ is the uniform intensity of magnetisation thereby established in the material along the direction of $\mathcal{H}$, and $\mathcal{B}$ is the uniform flux density, also established in that direction. From a logical standpoint, and in conformity with the I. E. C. ruling, the above equation should be interpreted as:

$$\mathcal{B} = \mu_0\,\mathcal{H} + 4\,\pi\,\mathcal{J} \qquad \text{gausses} \quad (2)$$

where $\mu_0$ is the permeability of free space (*gausses per oersted*) and is numerically equal to unity in the C. G. S. magnetic system.

If this interpretation is not read into equation (1), we have for the case of non-magnetic material, such as a vacuum,

$$\mathcal{J} = 0 \qquad (3)$$

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and
$$\mathcal{B} = \mathcal{H} \qquad (4)$$
or flux density $\mathcal{B}$ is physically, as well as numerically, equal to the magnetising force $\mathcal{H}$. If that were the case, one of the two quantities magnetising force and flux density would be superfluous, and either $\mathcal{B}$ or $\mathcal{H}$ could serve for both. The dislocation in electrotechnical literature involved by such a hypothesis would apparently be much greater than that entailed by these new I. E. C. resolutions.

If, however, the world's physicists should determine and declare at some future time, that the permeability $\mu_0$ of free space is a mere numeric without dimensions; so that $\mathcal{B}$ and $\mathcal{H}$ are physically identical, it would be incumbent upon electrotechnicians to reconsider these I. E. C. resolutions.

## THE I. E. C. RESOLUTIONS AND MAGNETIC OBSERVATORY MEASUREMENTS

In the determination and recording of the earth's magnetic field at the various magnetic observatories of the world, measurements are ordinarily made of the "field intensity," in its vertical and horizontal components. Since these measurements are made in air, which is a very feebly magnetic gaseous medium, it may be claimed that the quantity measured is a magnetic flux density $\mathcal{B}$ and not a magnetising force $\mathcal{H}$; although the numerical difference between the two is for ordinary purposes insignificant.

These component flux-density measurements are commonly expressed in *gammas* or $\gamma$; where $1\ \gamma = 10^{-5}$ *gauss*. The Greek letter gamma seems to have been chosen[1] on account of its resemblance to G, the initial letter of the name Gauss. The I. E. C. endorsement of the name *gauss* as the c. g. s. flux-density unit, thus conforms with this magnetic observatory usage.

## STEPS NECESSARY TO COMPLETE THE SERIES OF NAMES INTERNATIONALLY ASSIGNED TO THE C. G. S. MAGNETIC UNITS

Although the I. E. C. Resolutions of 1930, in pursuance of the Paris Congress Resolutions of 1900, provide names for the most important units of the C. G. S. magnetic system; yet there remain certain gaps in the terminology of the series, as the accompanying Table shows.

The question arises as to whether new internationally selected names are desirable to fill in the blanks of the Table. Opinions differ, not merely in different countries; but also in one and the same country. They vary over the whole range from the one extreme that all should be named, to the other extreme that none should be named; but that in each case the phrase c. g. s. unit of . . . should be used. It should, however, be pointed out that in the latter case, since there are two c. g. s. systems, the magnetic (with $\mu_0 = 1$ and $\kappa_0 = 1/v^2$) and the electric (with $\kappa_0 = 1$ and $\mu_0 = 1/v^2$), it is desirable to remove ambiguity, by using the somewhat lengthy phrase—c. g. s. magnetic unit of . . . .

TABLE I
C. G. S. MAGNETIC UNITS AND THEIR NAMES

| | Quantity | Symbol | Name | Date of International Adoption |
|---|---|---|---|---|
| 1 | Magnetomotive force | $\mathcal{F}$ | gilbert | 1930 |
| 2 | Magnetising force | $\mathcal{H}$ | oersted | 1930 |
| 3 | Magnetic flux | $\phi$ | maxwell | 1900 and 1930 |
| 4 | Magnetic flux density | $\mathcal{B}$ | gauss | 1900 and 1930 |
| 5 | Magnetic permeance | $\mathcal{P}$ | | |
| 6 | Permeability (absolute) | $\mu$ | | |
| 7 | Magnetic reluctance | $\mathcal{R}$ | | |
| 8 | Magnetic reluctivity | $\nu$ | | |
| 9 | Magnetic pole strength | $m$ | | |
| 10 | Intensity of magnetisation | $\mathfrak{J}$ | | |

In the writer's opinion, at least one of the blanks in Table I should be filled in, by the international adoption of the name for the c. g. s. unit of magnetic reluctance $\mathcal{R}$. It is often desirable to develop the complete expression for magnetic Ohm's law $\phi = \mathcal{F}/\mathcal{R}$, with names for all three units. With the name of the reluctance unit adopted, it would not be necessary to adopt a special name for the unit of reluctivity $\nu$. Just as the c. g. s. unit of resistance $R$ under the provisional name *abohm*, gives rise to the name for the c. g. s. unit of resistivity $\rho$ under the derivation *abohm-cm.*, so any name for the c. g. s. magnetic unit of reluctivity can be derived by adding (— cm.) to the adopted c. g. s. magnetic unit of reluctance.

Since reluctance is magnetomotive force per unit of flux, a temporary name for the unit of reluctance, until international action may have been taken, is the *gilbert per maxwell*. In the same way, those who for any reason may prefer not to use the I. E. C. name of *oersted* for $\mathcal{H}$ may correctly employ the longer term—*gilbert per cm.*, and likewise those who prefer not to use the I. E. C. name *gauss* for $\mathcal{B}$ may correctly employ the longer term—*maxwell per sq. cm.*

## THE PRACTICAL SYSTEM OF MAGNETIC UNITS

By its resolution to adopt the "practical" unit of magnetic flux, ($10^8$ *maxwells* or a *maxwell-eight*), under the title *pramaxwell*, together with the availability of the prefix *pra* for converting c. g. s. magnetic unit names into corresponding practical unit names, the I. E. C. has sanctioned the use of practical magnetic units, in response to a proposition from the Italian National Committee, at Bellagio, in 1927.

On this basis, a conducting loop has one volt induced in it, when it is threading magnetic flux uniformly at the rate of one *pramaxwell per second*.

It is important to consider the possibilities presented by this international recognition of a practical magnetic unit. As early as 1891, a committee of the American

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[1] Bibliography 24.

Institute of Electrical Engineers recommended for international consideration a series of magnetic units in the practical system; but the recorded opposition of the Chicago Congress, in 1893, to the suggestion, caused the plan to be set aside in favor of international magnetic units in the c. g. s. magnetic system. After nearly forty years, the I. E. C. action of 1930 has restored a practical magnetic unit to good standing, if it can justify itself in the opinion of electrotechnicians throughout the world. The immediate advantage of the *pramaxwell* is, of course, that in the fairly numerous working formulas of electrical engineering connecting induced voltages with magnetic flux, the numerical coefficient $10^8$ can ordinarily be eliminated and dispensed with by expressing the flux in *pramaxwells* instead of in *maxwells*. Some consider that this is a sufficient justification for the adoption of the *pramaxwell,* without extending the practical system any further. On the other hand, a single isolated magnetic unit in the practical system has less chance of proving its utility, than if it forms a member of a practical series.

What advantages might be secured from the adoption of a complete series of magnetic units in the practical system?

As an answer to this question, it has been pointed out by various writers, that if the magnetic units in the practical system were suitably adopted, the practical system would be converted into an absolute system independent of the parent c. g. s. system. Instead of defining the *volt* as $10^8$ c. g. s. magnetic units of e. m. f., the *ohm* as $10^9$ c. g. s. m. u. of resistance, and so on, these various practical units would be the respective fundamental units of e. m. f., resistance, etc., in the comprehensive electrodynamical system to which they all belonged. At present, this desirable condition does not hold; because the *volt, ohm* and *ampere,* etc., may be regarded as belonging to any one of a series of systems, such as the quadrant-eleventh-gram-second system of Maxwell, the meter-kilogram-second system of Giorgi, or the cm-gram-seven-second system[2] of Dellinger, Bennett, Karapetoff, and Mie. In each of these cases, the *watt* is the mechanical power required to accelerate the unit of mass with the unit of acceleration: *i. e.,* the eleventh-gram accelerated one quadrant per second$^2$, or the kilogram one meter per second$^2$, or the gram-seven (ten metric tons) one centimeter per second$^2$. Consequently if the *pragauss,* as the practical unit of flux density were internationally adopted as one *pramaxwell per square quadrant,* ($10^{-10}$ gauss) the Maxwell system would be endorsed, if per square meter ($10^4$ gauss), the Giorgi system would be endorsed, and if per square centimeter ($10^8$ gauss), the Dellinger-Bennett system would be endorsed. It is evident that while the adoption of the *pramaxwell* is a relatively simple matter, and does not involve entanglement with any particular dynamical system, the adoption of the *pragauss* as the *pramaxwell* per unit area, would logically involve association with a particular dynamical system.

The adoption of the *pragilbert* as the practical magnetic unit of magnetomotive force involves another question; namely, whether the practical system should be "rationalised" or not?

## RATIONALISED UNITS

Up to the present point of development, the practical volt-ampere-ohm system of units is neutral, being neither rationalised nor unrationalised; but the adoption of either the practical unit of m. m. f. or of the practical unit of flux density, would logically determine which of the two conditions should prevail. It was Heaviside who first drew attention[3] to the fact that the units in the c. g. s. system were so defined and adopted that a large number of formulas dealing with electro-geometrical problems of the rectilinear type, such as the capacitance of a slab condenser, prominently included the spherical factor $4\pi$, whereas corresponding problems of a spherical type, such as the capacitance of a spherical condenser, wherein such a factor might be expected to occur, did not include it. He proposed to rectify this inconsistency by revising and rationalising the fundamental definitions of the units and their dependent formulas; but the method which he advocated for doing this would have involved changing the magnitudes of the units. It would have been necessary to recalibrate all or nearly all working standard ohms, voltmeters, ammeters, etc.—a manifestly forbidding proposition. It has since been pointed out, however, by various writers,[4] that the advantages of rationalisation can be secured without changing any existing practical units or standards, by taking the factor $4\pi$ out of the unit definition of m. m. f. and inserting it into the unit definitions of permeance and reluctance, thereby keeping the unit of flux unchanged. This would, however, involve other corresponding changes in fundamental formulas.

## DOUBTFUL ADVANTAGE OF ATTEMPTING TO RATIONALISE THE C. G. S. SYSTEM NOW

At the present time, it seems very doubtful whether attempts could usefully be made to rationalise the c. g. s. system by taking the $4\pi$ out of m. m. f. and putting it into permeance. The Paris Congress of 1900 opposed the plan, and the I. E. C. Conference of 1930 endorsed the *gilbert* as the simple unrationalised c. g. s. unit of m. m. f. at the value of the $4\pi$th of an abampere-turn (0.07958), or the $10/(4\pi)$ of an ampere-turn (0.7958). These are good reasons for leaving the c. g. s. system in its classical unrationalised state.

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[2] Bibliography 8, 10, 13, 14, 15, 17, 18.

[3] Bibliography 3.

[4] See discussion by Bennett of bibliography 25, TRANS. A. I. E. E., April 1930, Vol. 49, p. 497.

## Reasons for Rationalising the Practical Magnetic Units

Although the c. g. s. magnetic units remain unrationalised, there is no reason why the practical magnetic units should not be rationalised if it were agreed to be advisable to do so internationally.

Table II presents a few magnetic-circuit formulas, under both unrationalised and rationalised forms, in parallel columns, for comparison. It will be seen that in case No. 1, which is the fundamental formula of the c. g. s. system, representing the repulsive force between two equal positive poles, the unrationalised formula is simpler than the rationalised formula. In all the other cases, however, the rationalised formula is the simpler and more logical.

Table II
Magnetic—Circuit Unit Systems

| | Unrationalised | Rationalised | |
|---|---|---|---|
| 1. The force between two like poles, each of strength $m$ at distance $r$, in a medium of permeability $\mu$, is: | | | |
| | $F = \frac{m^2}{\mu r^2}$ | $F = \frac{m^2}{4 \pi \mu r^2}$ | (5) |
| 2. The magnetomotive force of a coil of $N$ turns, carrying a current $I$, is: | | | |
| | $F = 4 \pi N I$ | $F = N I$ | (6) |
| 3. A magnetic pole of strength $m$ would emit a magnetic flux $\phi$ of: | | | |
| | $\phi = 4 \pi m$ | $\phi = m$ | (7) |
| 4. The mechanical work done by an active coil of steady m. m. f. $\mathfrak{F}$ during a movement which changes by $\phi$ units the total extraneous flux linked with it, is: | | | |
| | $W = \frac{\mathfrak{F} \phi}{4 \pi}$ | $W = \mathfrak{F} \phi$ | (8) |
| 5. The work done in carrying a magnetic pole of strength $m$ once around a current of strength $I$, is: | | | |
| | $W = 4 \pi m I$ | $W = m I$ | (9) |
| 6. The tension or tractive force between opposed parallel pole faces per unit of active surface area, carrying uniform flux density $\mathcal{B}$, if $\mu_0$ is the permeability of free space, is: | | | |
| | $f = \frac{\mathcal{B}^2}{8 \pi \mu_0}$ | $f = \frac{\mathcal{B}^2}{2 \mu_0}$ | (10) |
| 7. The magnetic energy per unit volume of a medium of permeability $\mu$, carrying uniform flux density $\mathcal{B}$, is: | | | |
| | $w = \frac{\mathcal{B}^2}{8 \pi \mu}$ | $w = \frac{\mathcal{B}^2}{2 \mu}$ | (11) |
| 8. The hysteretic work per unit of volume and per cycle, of a magnetisable material subjected to cyclic magnetisation, is: | | | |
| | The area of the Ewing loop in $\mathcal{H}\ \mathcal{B}$ units, divided by $4 \pi$. | The area of the Ewing loop in $\mathcal{H}\ \mathcal{B}$ units. | |
| | $w = \frac{1}{4 \pi} \int \mathcal{H} . d\mathcal{B}$ | $w = \int \mathcal{H} . d\mathcal{B}$ | (12) |

A great advantage of the rational series is that its unit of m. m. f. is the current-turn itself and not the 4 $\pi$th part, or 0.0795775th of a current-turn in any system. In the practical volt-ampere-ohm system, the rationalised unit of m. m. f. becomes the ampere-turn, which is self explanatory and for which no special name is needed. Otherwise a *pragilbert* based on the gilbert, would be the 4 $\pi$th part of one ampere-turn and would be unrationalised. If therefore the ampere-turn came to be adopted as the practical unit of m. m. f., the practical magnetic system would logically become rationalised. In view of what has been shown by Heaviside, Lorentz, and other authors, as to the advantages of rationalised units, it is the opinion of the present writer that they should meet with general favor, and ultimately become internationally adopted. It appears that this would also involve the rationalisation of the electrostatic units, as an automatic and equally advantageous consequence. Thus, the total electrostatic flux in a condenser would become numerically equal to its charge in *coulombs.*

It may be noted that in the books and papers that have already been published in the m. k. s. and c. c. g. s. systems, their units are rationalised.

## Need for Dissemination of Literature on Serviceability of Practical Magnetic Units; but no Need for Action being taken on Them in Near Future

Table III presents a series of rationalised magnetic units in the m. k. s. and c. g. s. s. practical systems, columns IV and VI give provisional names of the units; while columns V and VII give the number of the basic c. g. s. magnetic units in each practical unit. Thus there are $10^4$ c. g. s. units of flux density or gausses in the *pramaxwell per square meter,* and $10^8$ gausses in the *pramaxwell per square centimeter.*

Before attempting to secure international action leading to a choice between the m. k. s. and c. g. s. s. practical systems of magnetic units, it is desirable that their relative advantages should be generally discussed and more widely known. For this purpose, it would be useful to have papers or primers published indicating the formulas and treatment of practical problems in each. In the writer's opinion, their respective advantages are fairly well balanced, so long as the formulas and problems relate to simple magnetic and electrostatic circuits. In more general cases, however, the unit of mass of $10^7$ grams in the c. g. s. s. system places it at a great disadvantage compared with the unit mass of $10^3$ grams or one kilogram in the m. k. s. system.

For the present, it seems desirable to allow time for the practical units to develop along the lines of individual preference. It is evident from Tables I and III that magnetic-circuit computations can continue to be carried on without difficulty in the classical c. g. s. system, especially if an international unit of reluctance is added to the list. Writers desiring to use either of the two rival practical systems have sufficient units already available for ordinary use, although some of the names are lengthy, provisional, and open to criticism.

TABLE III
MAGNETIC UNITS IN THE RATIONALISED M. K. S. AND C. G. S. S. SYSTEMS

| | | | $L = 1$ m | $M = 10^3$ gm. | $L = 1$ cm. | $M = 10^7$ gm. |
|---|---|---|---|---|---|---|
| | Unit | | M. K. S. (Giorgi) | | C. G. S. S. (Dellinger-Bennett) | |
| I | II | III Symbol | IV | V C. G. S. U. | VI | VII C. G. S. U. |
| 1 | Magnetomotive force | $\mathfrak{F}$ | ampere-turn | $4\pi/10$ | ampere-turn | $4\pi/10$ |
| 2 | Flux | $\phi$ | pramaxwell | $10^8$ | pramaxwell | $10^8$ |
| 3 | Magnetising force | $\mathcal{H}$ | ampere-turn/m | $4\pi/10^3$ | ampere-turn/cm | $4\pi/10$ |
| 4 | Flux density | $\mathcal{B}$ | pramaxwell/sq. m | $10^4$ | pramaxwell/sq. cm | $10^8$ |
| 5 | Space permeability | $\mu_0$ | henry/m | $10^7/4\pi$ | henry/cm | $10^9/4\pi$ |
| 6 | Permeance | $\mathcal{P}$ | henry | $10^9/4\pi$ | henry | $10^9/4\pi$ |
| 7 | Space reluctivity | $\nu_0$ | yrneh-m | $4\pi/10^7$ | yrneh-cm | $4\pi/10^9$ |
| 8 | Reluctance | $\mathcal{R}$ | yrneh | $4\pi/10^9$ | yrneh | $4\pi/10^9$ |
| 9 | Inductance | $\mathfrak{L}$ | henry | $10^9$ | henry | $10^9$ |
| 10 | Magnetisation | $\mathfrak{I}$ | pramaxwell/sq. m | $10^4/4\pi$ | pramaxwell/sq. cm | $10^8/4\pi$ |
| 11 | Pole strength | $m$ | pramaxwell | $10^8/4\pi$ | pramaxwell | $10^8/4\pi$ |
| 12 | Magnetic moment | $\mathfrak{M}$ | pramaxwell-m | $10^{10}/4\pi$ | pramaxwell-cm | $10^8/4\pi$ |

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## Discussion

**S. L. Gokhale:** The paper under discussion divides itself naturally into two parts.

1. A summary of what the I. E. C. decided during the last meeting at Oslo, July 1930.

2. The author's suggestions and recommendations as to what should be done next.

With reference to the first item, it is gratifying to note, that in supporting the hypothesis, that the permeability of space is a dimensional quantity, the I. E. C. has qualified the recommendation with the limiting clause, that the hypothesis is accepted for "electrotechnical purposes." To the proposition thus stated, there can be no objection even by one who believes space permeability to be non-dimensional. It is, in my opinion, the best possible compromise under the circumstances.

For many years, the scientists dealing with electromagnetic phenomena have been divided into two groups, according to their conception of the nature of magnetic field. According to magnetostatic conception, which is generally accepted by physicists, permeability is a non-dimensional quantity.

According to the magnetodynamic conception which is almost unanimously accepted by the electrical engineers, permeability is a dimensional quantity. No crucial test to judge the validity of these two conceptions has yet been formulated, and no rational